

New Technologies in VLBI
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When you wish upon a star: Future developments in astronomical VLBI.

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Abstract. In this paper, I present the likely technological development of VLBI, and its impact on the astronomical community over the next 1-5 years. VLBI is currently poised to take advantage of the rapid development in commercial off-the-shelf (COTS) PC-based products. The imminent deployment of disk-based recording systems will enable Gbps data rates to be achieved routinely by both cm and mm-VLBI networks. This, together with anticipated improvements in collecting area, receiver systems and coherence time is set to transform the performance of VLBI in terms of both baseline and image noise sensitivity. At the same time the feasibility of using fibre based communication networks as the basis for production, real-time VLBI networks will begin. Fantastic new correlator output data rates, and the ability to deal with these via powerful PC clusters promises to expand the typical VLBI field-of-view to scales previously reserved for connected, short baseline interferometers. By simultaneously sampling the *summed* response of all compact radio sources within (and indeed beyond) the half-power point of the VLBI telescope primary beam, simple self-calibration of the target field will *always* be possible at frequencies below a few GHz. Unbiased, broad-band continuum surveys will be conducted over huge areas of sky, and (red-shifted) spectral-features will be detected too. By the end of the decade the microJy radio sky will be accessible to VLBI: dozens of sources will be simultaneously observed, correlated, detected and fully analysed all within the same day.

1. Introduction

In this paper I review the possible future development of astronomical Very Long Baseline Interferometry (VLBI). My analysis is very much user-driven — the terms of the review being made via a user-based “wish list”. The focus falls on several areas that are important to the astronomical community, and which are likely to be addressed by the new technologies presented throughout this volume. A similar paper is presented by Schlüter (this volume) regarding likely advances in Geodetic VLBI activities.

Naturally, some of the points addressed here represent areas in which I am personally interested or involved. While these may receive extra attention, I have tried to maintain a reasonable balance throughout the text. The astronomical wish-list thus includes:

- vastly improved raw baseline and image sensitivity,
- extended frequency coverage & agility,
- enhanced image fidelity,
- more flexible, robust and reliable VLBI data, including auxiliary (calibration) data,
- sharper spatial and spectral resolution,
- fantastic new correlator capacities & sufficiently capable offline computing resources (including GRIDs) to analyse the data,
- access to a significantly *deeper* & *wider* field-of-view,
- the introduction of automatic data calibration and new analysis techniques.

I will review each of these areas in turn, and consider the prospects for possible improvements. It should be noted that this review is made at a crucial juncture in the development of VLBI – in particular the rapid development of commercial off-the-shelf (COTS) PC-based products are expected to make a substantial impact in many areas of VLBI that have previously enjoyed only incremental advances. These new developments include: flexible digital signal processing, disk-based data recording, data transfer via transnational, broad-band, internet communication networks and capable (offline) computing resources via (Linux) PC clusters. Over the next decade, the opportunities for making substantial progress are excellent.

2. VLBI Sensitivity

In VLBI (and radio interferometry in general) the image and baseline sensitivity (σ_I and σ_B respectively) are dependent on several different parameters. Two of these are specific to the antenna - the effective collecting area (A_e , m²) and the antenna system noise (T_{sys} , Kelvin). In addition, sensitivity to broadband continuum radio emission is determined by the output fluctuations of the receiver, and so the signal-to-noise ratio is proportional to the square root of both the spanned observing bandwidth ($\Delta\nu$ Hz) and the total (coherent) integration time (τ , seconds). In SI units the 1σ baseline sensitivity is given by:

$$\sigma_B = \frac{2k\eta_b}{\sqrt{2\Delta\nu\tau}} \sqrt{\frac{T_{sys1}T_{sys2}}{A_{e1}A_{e2}}} \quad (1)$$

where k is Boltzmann's constant & η_b accounts for various losses (see Walker et al. 1988 for more details). Note that the baseline sensitivity improves (i.e. σ_B decreases) proportionally with the geometric average of the effective area of the two telescopes, and inversely proportional to the geometrical average of their system temperatures.

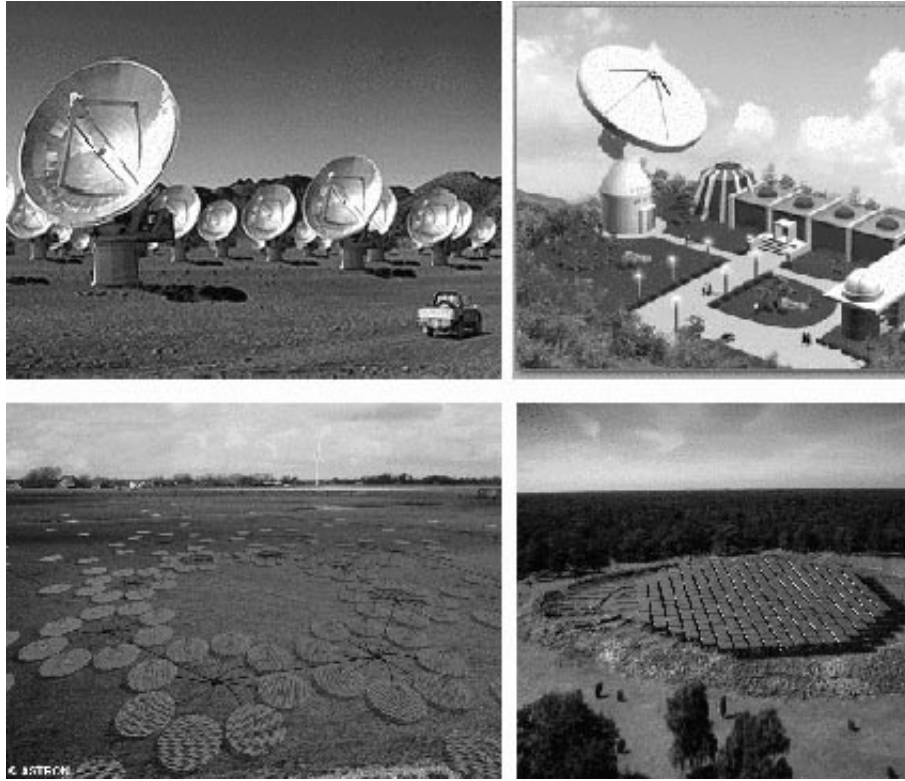


Figure 1. Large gains in collecting area can be expected in mm-VLBI with the incorporation of ALMA (top left) and other new mm-capable telescopes (e.g. the KVN top right). The construction of LOFAR (bottom left) is expected to lead to a resurgence in interest in meter-VLBI. On longer times-scales, the SKA (bottom right) will lead (either directly or indirectly) to a substantial increase in the collecting area available to cm-VLBI.

Similarly, the 1σ r.m.s. image noise (assuming optimal data weighting – natural weighting) is given by:

$$\sigma_I = \frac{2k\eta_b}{\sqrt{\Delta\nu\tau}} \sqrt{\frac{1}{(\sum_i \frac{A_i}{T_{sysi}})^2 - \sum_i (\frac{A_i}{T_{sysi}})^2}} \quad (2)$$

It is clear from these expressions that improvements in sensitivity can be obtained via four (largely) independent parameters: (i) increased collecting area, (ii) lower noise receiver systems, (iii) longer coherence times & (iv) larger total observing bandwidths.

2.1. Collecting Area

Any increase in collecting area is expected to be incremental at cm wavelengths but over the next decade, significant gains could be made at both higher and lower frequencies (see Figure 1). In particular, mm-VLBI has much to gain by incorporating ALMA within existing networks (see Alef et al. this volume) and similarly low-frequency (meter wavelength) VLBI is bound to be stimulated by the construction of the Low Frequency Array (LOFAR). mm-VLBI (and to a lesser extent cm-VLBI) will also benefit from the addition of new telescopes in Asia (VERA and the KVN – see Minh et al., Kobayashi et al. and Sassao et al., this volume) and in Europe (the Yebes-OAN 40-m telescope and the IRA 64-m Sardinian Radio Telescope). A significant increase in collecting area for cm-VLBI will have to await the construction of the next generation cm-wave radio telescope – SKA (see Gurvits this volume).

2.2. Receiver Noise Temperature

Both cm and mm-VLBI are likely to see significant progress in the area of improved receiver technology. For example, the *e*-MERLIN array (see Muxlow et al. this volume) will employ 4-8 GHz receivers that are expected to be a factor of two better than the current (33 K) systems. Even larger factors of improvement can be expected at mm-wavelengths (see Figure 2).

2.3. Coherence Time

cm-VLBI Through the application of phase-referencing techniques (Beasley & Conway 1995), it is now possible to extend the coherence time of a cm-VLBI array across the entire duration of the observations. This permits the routine detection of relatively faint (sub-mJy) radio sources (e.g. Garrett et al. 2001) at wavelengths up to $\lambda 1$ cm. These phase-reference images are often dynamic range limited at the level of 20:1, in-beam phase-referencing removes such limitations and its use (at cm wavelengths) is generally more applicable than usually understood. At $\lambda 18$ cm for example, in-beam phase-referencing is even possible for very large telescopes, provided wide-field techniques are used to combine the total signal from all compact sources in the primary-beam (see section 7 for more details). This permits *in-beam self-calibration* to be used in *all* circumstances (*i.e.* any target field) – an important new capability, and one that should be familiar to users of connected arrays.

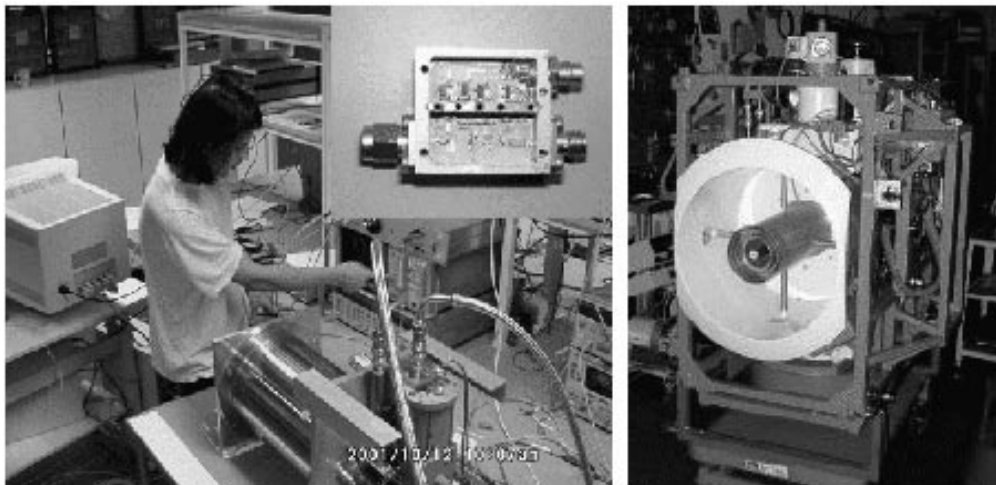


Figure 2. Low-noise amplifiers (such as the broad-band 4-8 GHz OSO/Chalmers system shown left) are set to make significant improvements in receivers to be developed for cm but in particular mm and sub-mm wavelengths. Low-noise frequency flexible systems (e.g. the WSRT MFFE system shown right) are now common at cm-wavelengths.

mm-VLBI In recent years significant advances have been made in improving the coherence times at mm-wavelengths. VERA for example will use a multi-beam system that simultaneously permits one beam to be directed at the target, and another to a nearby calibrator. Phase corrections from the calibrator are thus continuously applied to the target without any source switching.

However, one limitation of dual-beam phase correction at mm wavelengths is that the number of bright mm-calibrators is extremely limited, and thus often involves target-calibrator separations on the scale of several degrees. In these cases, the effects of spatial interpolation errors (across the sky) cannot be ignored. Another method which addresses this problem (and one which is showing enormous promise), is to derive mm-wave phase corrections via a cm-wave reference source (see Asaki et al. 1998; also Sasao et al., and Alef et al. this volume). This method relies on the fact that the tropospheric delay is independent of frequency. In its simplest form, multi-frequency co-axial feed systems can be used to simultaneously observe the target, and phase corrections derived at say 22 GHz are applied (after appropriate scaling with frequency and correcting for any antenna based phase-offsets) to much higher frequencies (e.g. 100 GHz). Note that some relative astrometry is also preserved - the position of the cm-wavelength “core” being the reference point. It is clear that this technique might also be usefully employed for high-frequency Space VLBI missions, such as VSOP2 (see Hariyashi et al. this volume).

2.4. Observing Bandwidth

The promise of access to much broader bandwidths is expected to explode in the next decade. The consequences for both mm and cm-VLBI are significant, especially for cm-VLBI where gains in other areas related to sensitivity will be modest. Currently 256 Mbps is just about the maximum data rate that can be currently sustained in most VLBI networks. For the European VLBI Network (EVN, see www.evlbi.org) the limitation is not a technological one (512 Mbps recording is now routinely performed) but the availability of thin-tapes. Within the next 2 years sustained data rates of 1 Gbps will certainly be available to VLBI users. This will lead to a factor of two better sensitivity for both mm and cm-VLBI networks. The longer term aim must be to attain data rates of several Gbps, reaching tens of Gbps by the end of the decade. This can be utilised by both mm and cm-VLBI networks, in the latter case not just for bandwidth but in order to employ multi-bit signal representation required by RFI mitigation algorithms.

PC disk-based recorders The promise of access to much broader bandwidths is expected to explode in the next decade (see Figure 3). The consequences for both mm and cm-VLBI are significant, especially for cm-VLBI where gains in other areas will be modest.

The maximum total bandwidth currently used in VLBI is ~ 64 MHz (in each of 2 polarisations), corresponding to a total data rate of 512 Mbps (2-bit signal representation and Nyquist Sampling). The replacement of the current generation of magnetic tape recorders, with PC-based disk recorder systems (see Whitney et al., Parsley et al., Romney et al., Kondo et al. this volume) is expected to take place over the next few years. By employing commercial PC hardware, the VLBI community will be able to take advantage of the rapid technological development in this area. In principle, a doubling of the data capacity of PC-based recorders might be expected every few years. Since the Mk5A system can already record at 1 Gbps (see Figure 3), data rates in excess of this are likely to be possible on relatively short time-scales. In addition, the cost of disks will continue to shrink, at least in real terms (i.e. for a given storage capacity).

Real Time, Optical Fibre-based VLBI networks An alternative (or perhaps successor) to disk-based recorder systems is the connection of VLBI networks via optical fibres (see Parsley & Whitney this volume & Figure 3). Fibre communication networks are ideally suited to the real-time transfer of huge amounts of data over long distances. The adoption of direct fibre connections by *e*-MERLIN (see Muxlow this volume) signals the progress that is being made in this area. As the costs of these networks continue to fall, and as commercial networks become more flexible, the introduction of a real-time VLBI system is a reasonable goal to pursue.

In Europe there are plans to demonstrate the feasibility of real-time VLBI using shared IP routed networks (e.g. GÉANT). A proof-of-concept test programme (to be conducted over the next 1-2 years), aims to connect together directly, at least 4 European telescopes to the EVN correlator at JIVE (see Parsley this volume). Each telescope will generate up to 1 Gbps data streams,

and these will feed into the EVN correlator at JIVE (see Parsley et al. this volume). The idea is to correlate the data with minimal buffering at either end of the fibres. The provision of local loops (last mile connections) to the telescopes and correlator is the critical item. Local loops are in place at Dwingeloo (JIVE) and Torun. Westerbork is to be connected in mid-2003, and negotiations are on-going at other EVN sites, in particular Jodrell Bank, Effelsberg, Medicina, Onsala and Metsahovi.

Technical issues that need to be thrashed out include the quality of service required by VLBI, and the amount of buffering required at the telescopes and correlator. Assuming the first tests are successful, the ambition in Europe is to investigate “production” real-time VLBI networks, and to broaden participation to include Asia, North-America and Africa.

Implications for VLBI Back/Front-end systems & Correlators Both fibre and PC-based VLBI networks will permit routine Gbps VLBI observations to be made in the course of the next few years. Developments beyond this requires (in many cases) a replacement to the current VLBI data acquisition system (in particular the expensive, and now obsolete, analogue Base Band Converters - BBCs) with cheaper and more flexible digital replacement systems. The interest in the latter topic is witnessed by the activity reported in this volume (see Ferris et al., Tuccari et al., Ying et al., Roh et al., Kondo et al., Koyama et al., Iguchi et al). However, discussion about the necessity to broad-band front-end telescope receiver systems was limited.

Correlation of Gbps data stream is also a problem. For example, the EVN MkIV correlator at JIVE can currently handle 16 telescopes at 1 Gbps or (potentially) 8 telescopes at 2 Gbps. Data rates in excess of this would require a new, more capable correlator, similar to that being developed for the EVLA and *e*-MERLIN (see Carlson et al. this volume).

It is clear that to take full advantage of the increasing capacity of both disk and fibre-based systems, considerable efforts must begin *now*, in terms of new receiver systems, replacement back-end data acquisition racks and future VLBI correlator developments.

2.5. Overall Sensitivity Gains & Image Fidelity

It is clear that both cm-VLBI and in particular mm-VLBI can expect to make considerable gains in terms of collecting area, bandwidth (data rates), receiver noise temperature and techniques to extend the coherence time of the data.

For continuum cm-VLBI a total gain in sensitivity of at least 5 seems plausible over the next few years. In principle, noise levels at microJy and even sub-microJy levels should be attainable (see Figure 4) by Global VLBI arrays. An important provision is that both the EVN and Very Long Baseline Array (VLBA, see www.nrao.edu) adopt the same fully compatible, next generation (disk-based) data acquisition systems. It is good to see that the Global VLBI Working Group (that also met here in Korea) have already started to worry about these very issues.

In the case of mm-VLBI, at least an order of magnitude improvement would not be surprising. In addition, since mm-VLBI's gains will also include addi-

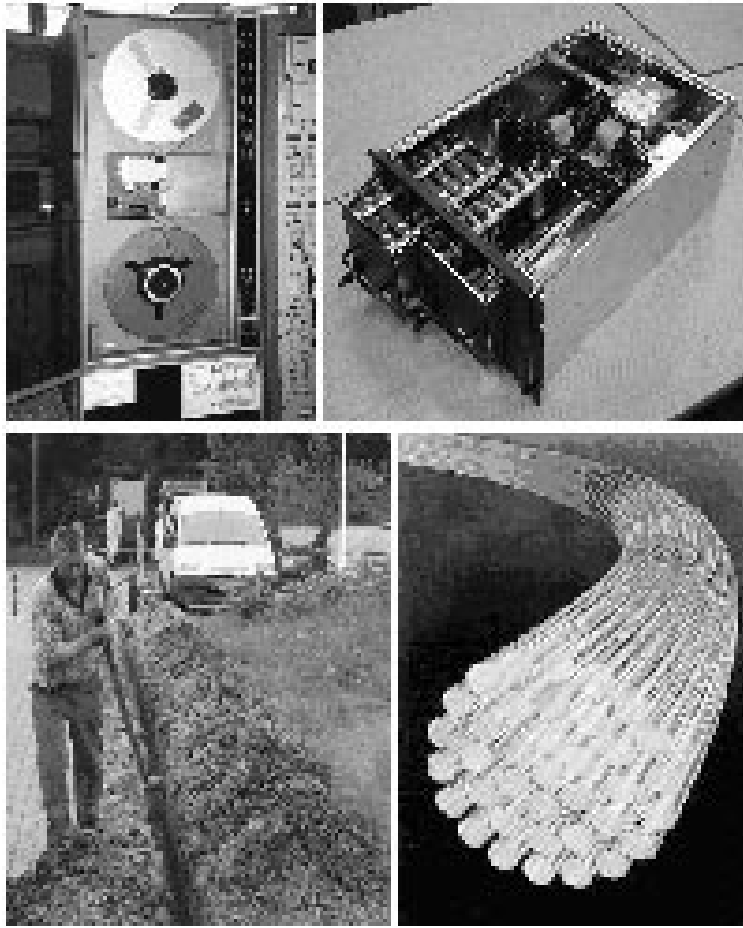


Figure 3. Magnetic tape technology (top left) is now being replaced by PC disk-based (Mk5) recording systems (top right). Real-time VLBI using optical fibre networks must be the long-term goal (bottom right). The EVN correlator at JIVE is already connected by a fibre network that currently provide Gbps data rates but will be easily upgraded to permit even larger data rates to be employed.

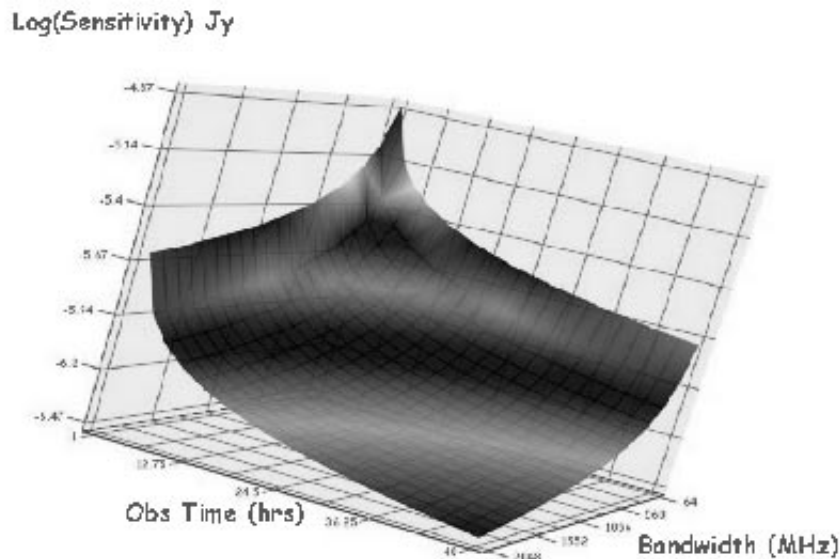


Figure 4. The sub-microJy sensitivity of the *e*-EVN as a function of bandwidth and integration time.

tional collecting area and improved receiver systems, spectral-line studies also stand to benefit, not just standard continuum observations.

So far we have neglected to mention that any increase in observed bandwidth will also (assuming the data remains unaveraged in frequency) result in an improvement in uv-coverage and thus image fidelity. This is particularly the case for cm-VLBI where the fractional bandwidth should soon approach unity and Multi Frequency Synthesis (MFS) techniques can be employed to take full advantage of this. Figure 5 presents the uv-coverage of the *e*-EVN assuming a total bandwidth of 2 GHz per polarisation.

3. Frequency Coverage/Flexibility, Receiver Design & RFI

An important development in recent times, has been the construction of front-end receivers that can be instantaneously tuned over a wide-range of sky frequency (e.g. from 1-10 GHz in the case of the Allen Telescope Array). In these systems, several bands (each ~ 1 GHz in extent) can then be selected individually and digitised. Systems like these need to be in place at VLBI telescopes if we are to fully capitalise on the expected increase in capacity of second generation disk and (first generation) fibre-based VLBI networks. However, in addition to sensitivity and image fidelity issues (see previous section), there is another astronomical motivation for instantaneous access to large swathes of bandwidth: Serendipitous VLBI spectral line surveys (e.g. HI in absorption). Already such surveys are being conducted by connected element arrays (e.g. Morganti & Garrett 2002) and as the field-of-view of VLBI observations increases (see section 6), VLBI can easily follow suit.

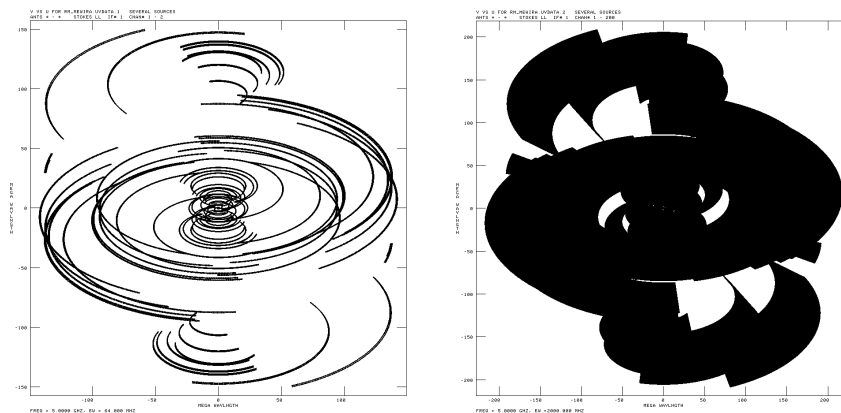


Figure 5. Left: The current uv-coverage of the EVN at $\lambda 6$ cm for a source located at $\delta = 30^\circ$. Right: the extended (almost full) uv-coverage of the eEVN for the same source, assuming a total bandwidth of 2 GHz per polarisation.

The effects of Radio Frequency Interference (RFI) will also become increasingly important as VLBI systems become more sensitive and observe larger bandwidths. Although RFI does not usually correlate on baselines > 10 km, local interfering signals are often so strong that they can easily saturate receivers, and dominate the antenna system noise. In addition, as a noise source, RFI is often extremely variable on time scales of a few seconds or less — tracking the telescopes calibration under such conditions is usually impossible. Real VLBI users are often sceptical of many RFI suppression techniques but at this meeting there were several good presentations that suggest there are more effective ways to counter RFI (e.g. Kesteven and Roshir this volume) than simply deleting the data. We had better start using these sooner, rather than later.

Rapid frequency switching is a routine observing mode for the VLBA. This capability is important for spectral index mapping studies but also increases the robustness and reliability of VLBI operations. Many of the telescopes in the EVN are now frequency flexible (see Figure 2) but only a few experiments have taken advantage of this facility so far. Rapid progress is expected to take place in this area over the next year.

Finally, polarisation purity is another topic that often gets ignored in VLBI receiver design. This is another area in which a homogeneous array such as the VLBA has a significant advantage. The current aim of the EVN is to produce $< 2\%$ cross-talk between left and right hand circular polarisation channels. Although many of the EVN telescopes are actually much better than this, some telescopes show cross-talk at the level of $\sim 15\%$! These include special cases such as the WSRT phased-array. These figures can limit the dynamic range of total intensity images of even moderately bright radio sources, and for polarisation studies, the level of impurity is large enough that second order calibration corrections (usually assumed to be negligible) must be accounted for.

4. Sharper Resolution, Space VLBI and SKA Configurations

When it comes to resolution VLBI astronomers are a difficult lot to satisfy. Their desire for increasingly better resolution forces them to move towards higher frequencies and/or longer baselines. This is an effect that was clearly demonstrated at this meeting. In particular, next generation orbiting VLBI telescopes (e.g. VSOP-2) combine both these elements together, employing only high-frequency receivers (8, 22 & 43 GHz), and baselines between 3 – 5 Earth radii (see Hirabayashi et al. and Mochizuki et al. Gurvits et al. this volume). RadioAstron goes a step further with even longer baselines being proposed.

I feel it necessary to introduce a note of caution at this point. As we move towards higher frequencies and longer baselines, AGN science clearly stands to benefit. However, other areas of growing importance are being neglected e.g. the study of SNe, SNR, micro-quasars, active stars, HI absorption, OH emission, starburst galaxies, high-z star-forming/AGN systems etc. These require high resolution too - perhaps third generation Space VLBI missions will be able to address these requirements too.

Angular resolution is also a hot topic in the discussion of array configurations for the SKA (see Gurvits this volume). Plans for the next generation of ground and space based astronomical observatories, will provide much higher resolution (approaching traditional milliarcsecond scales) for sub-mm, IR, optical/UV and x-ray astronomers. This, together with source confusion is likely to see the SKA deployed with complimentary baselines in excess of 1000 km (Garrett et al. 2002).

5. VLBI Calibration, auxiliary data products and automatic data (pipeline) analysis

Over the last 10 years the VLBA has set the standard in terms of generating accurate and homogeneous astronomical VLBI calibration data. Meanwhile the rest of us have been playing “catch-up”! The generation of such data is vital in order to make VLBI transparent to all astronomers (not just a few “black-belt” practitioners). In addition, it is necessary in order to obtain high-dynamic range images via both manual and automatic analysis paths (but especially the latter).

The EVN is beginning to get there - continuous system temperature data is now available, both as a function of time and frequency (see Figure 6). The calibration of the telescopes (via the NASA/GSFC Field System) is considerably improved, with lots of essential new features (see Himwich this volume). In addition, the EVN is now able to compare the pointing position of the telescope and the direction of the target source i.e. it is now possible to generate “flag files” that can be used to identify non-valid telescope data (see also Figure 6). Progress in this area was also reported by other arrays (e.g. the LBA, Tingay this volume).

As data sets become larger (see section 6 & 7) it will be necessary to automatically perform on-line calibration and data analysis. The EVN pipeline (Reynolds, Paragi & Garrett 2002) is the first step along this road. All EVN projects are now “pipelined” by default. The products include a set of AIPS calibration tables (a-priori calibration, fringe-fitting and self-calibration) and

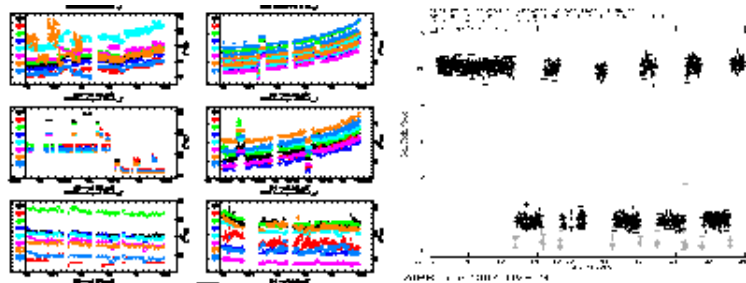


Figure 6. In the 1990's the VLBA set the standard for auxiliary data products. Other VLBI networks are only now catching up. Continuous TSYS (left) and the application of Telescope Flag files (right) are now routinely generated by the EVN.

various standard plots. As well as reducing the effort required on behalf of the astronomer, we also gain a much better understanding of the performance of the network. The default mode is only to pipeline data associated with calibrators but on request the target source can also be analysed. All astronomers can take advantage of the EVN pipeline - irrespective of their experience, affiliation or geographical location.

6. Field-of-View, Spectral-line & Fantastic Correlator output data rates

For a connected element array, the field-of-view is often set by the primary beam size of the individual telescope elements. For VLBI this is hardly ever the case. In VLBI, a more demanding limitation is set by the fine spectral resolution and short integration times that must be employed in order to circumvent *both* bandwidth smearing and time averaging effects. Since preserving the field-of-view scales (computationally) with baseline length *squared*, wide-field VLBI analysis places enormous pressure on offline computer resources (processing speed *and* disk space). These are many orders of magnitude greater than for short-baseline, connected arrays.

In the same vein, a VLBI field-of-view that is comparable with the primary beam of the individual telescopes, places demands on the correlator output data rate that are nothing short of “fantastic”. Pushed to their limits, current VLBI correlators are just about capable of providing sufficient resolution in both time and frequency (e.g. 0.5 sec integration time and 1024×62.5 kHz channels) to permit the inner 3 arcmin the telescope primary beam to be imaged out with full sensitivity at 1.4 GHz. This corresponds to a correlator output data rate (~ 1 Mbyte/sec) - well short of what is required to map-out the full (half-power point) primary beam of a 100-m, never-mind the much larger field-of-view associated with 25 or 32-m class telescopes.

The PCInt project currently being developed at JIVE (see Figure 7), will enable the EVN correlator to generate and handle output data rates as high



Figure 7. The EVN correlator at JIVE has been operational since the end of 1999. The PCInt project will enable the EVN correlator to generate and handle output data rates as high as 160 MBytes/sec or 13 TBytes/day. This will permit the full capacity of the correlator to be harnessed.

as 160 MBytes/sec or 13 TBytes/day. This will permit the full capacity of the correlator to be harnessed, permitting a spectral resolution of 8092 channels per baseline or integration times as short as 15 milli-seconds. PCInt will hugely expand the field-of-view of VLBI quite generally (not just the EVN), and will provide the capability to simultaneously map-out large swathes of the radio sky with milliarcsecond resolution.

Much finer spectral resolution is not only required to expand the field-of-view but it is also important for spectral-line studies. Often spectral-line projects have to trade spectral resolution for the number of telescopes, polarisation products etc. Many projects also require multiple-pass correlation because more than one spectral feature is present (and the correlator provides just enough resolution for one line in any given pass). In addition, broad-banding of connected interferometers (in particular the upgraded WSRT) has recently revealed some very broad HI absorption systems (e.g. Morganti et al. 2002), broad enough, that current VLBI correlators are inadequate to appropriately sample the full width of the line.

7. Deep, Wide-Field cm-VLBI Studies

The application of wide-field techniques to VLBI data analysis is fundamental to high resolution, deep field studies of the faint sub-mJy radio source population. That VLBI can make a contribution in this area was first demonstrated with the EVN 1.6 GHz observations of the Hubble Deep Field (HDF).

7.1. EVN Observations of the HDF

EVN 1.6 GHz observations of the HDF (Garrett et al. 2001) were the first VLBI observations of what is essentially a “blank field”, i.e. a region of sky, devoid of bright radio sources. The brightest source in the HDF-N (as measured by the WSRT and VLA) is a 1.6 mJy FR1 radio galaxy at $z = 1$. In addition, the

observations (correlated at the VLBA correlator in Socorro) employed wide-field techniques (1 sec integrations, 64×125 kHz channels) and it was thus possible to simultaneously image out the full field encompassed by the HDF-N (~ 6 sq. arcmin). Three sources were detected within this field (see Figure 8) - including the faintest source yet detected by VLBI - a 180 microJy AGN associated with a spiral galaxy (with a bulge) at $z = 0.96$.

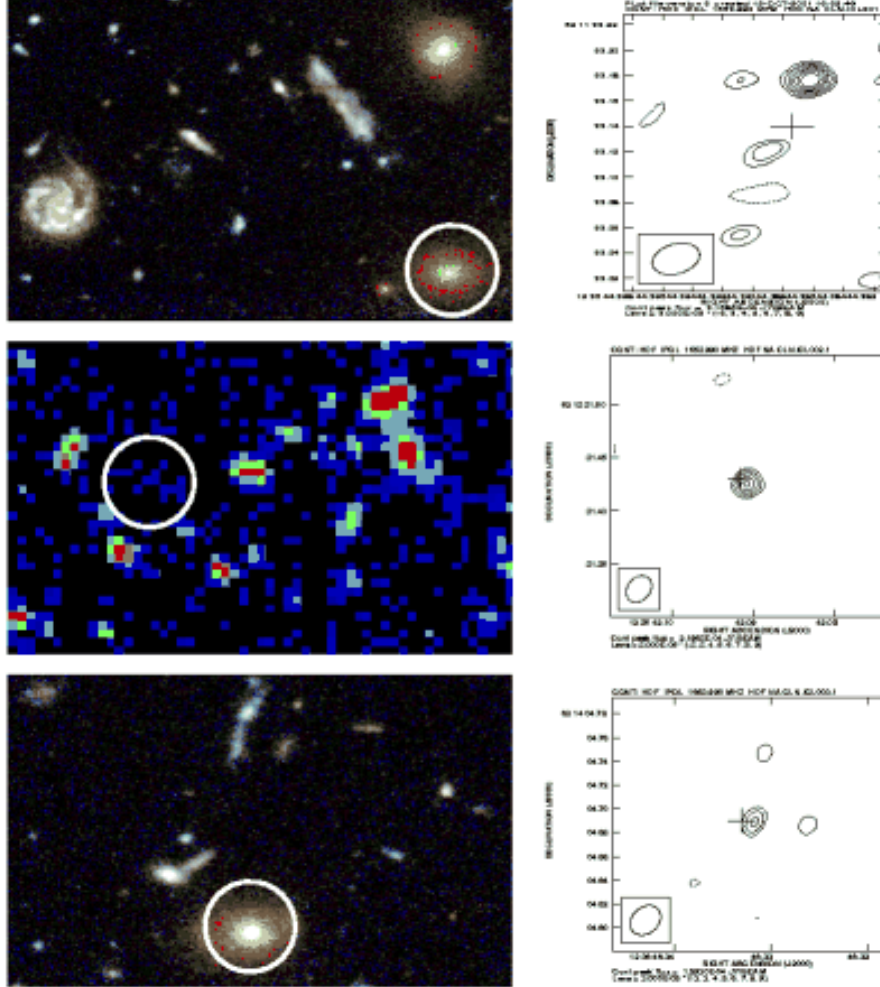


Figure 8. EVN detections in the HDF: the distant $z=1.01$ FRI (top), the $z=4.4$ dusty obscured starburst hosting a hidden AGN (middle) and the faint 180 microJy, $z=0.96$ AGN (bottom). Crosses represent the MERLIN-VLA positions for these sources.

7.2. Recent VLBA+GBT deep field results

The rms noise levels achieved by the EVN HDF-N observations were limited by phase errors introduced via conventional, external phase-referencing (switching) techniques. The field-of-view was limited by the frequency and time resolution that could then be achieved by the VLBA correlator.

Some recent VLBA+GBT deep field observations illustrate the gains to be made in employing “in-beam” phase referencing. Figure 9 shows the deepest VLBI images made to date (Garrett, Wrobel & Morganti in prep). The images (with an rms noise of 9 microJy/beam in the centre of the field) were made from a 1.4 GHz VLBA+GBT observing run (3×8 hours @256 Mbps). In-beam phase-referencing was used to provide essentially perfect phase corrections for this data set, and eight sources are simultaneously detected ($> 7\sigma$) within and outside the half-power point of the GBT primary beam. Of these eight sources, two sub-mJy sources are detected within the primary beam of the GBT, in addition to the in-beam phase reference calibrator (a compact 20 mJy source, first detected by Wrobel et al.). The images of sources far from the field centred are tapered, since the time/frequency sampling is only adequate for sources that lie within the primary beam of the GBT (the latter being centred on the VLBI phase centre).

The total (target) data set size is 60 Gbytes (0.5 secs integration, 1024×62.5 kHz channels). Images were made with the AIPS task IMAGR - dirty maps/beams of each sub-band (IF) for each epoch were generated blindly and then simply co-added together. Each postage stamp image took about 8 hours to produce on a dual (2 GHz) processor Linux box. The analysis of these data is on-going. For sources that were bright enough, CLEAN maps were produced by simply subtracting the dirty beam from the dirty image (AIPS task APCLN). More complicated tasks (e.g. IMAGR) involving a visibility based CLEAN are prohibitively expensive in terms of CPU requirements.

7.3. Lessons for the future

Phase-referencing no longer required at 1-3 GHz What is clear now, and what I would like to focus on in the final section of this paper, is that if the field of view of VLBI can indeed be expanded (see section 6 and the PCInt development at JIVE) then the whole concept of phase-referencing has to change - at least at frequencies below 3 GHz.

The reason for this is that if one can simultaneously sample the *summed* response of all compact radio sources within (and indeed beyond) the half-power point of the VLBI telescope primary beam, then simple self-calibration of the target field is *always* possible, essentially trivial, and can provide (essentially) perfect phase corrections to the data. Phase-referencing is still required (to some extent) in order to preserve the astrometry and to improve the coherence time of the data - *before* self-calibration of the target field is attempted. In simple terms, at frequencies 1-3 GHz (perhaps even higher or lower) a VLBI observation (correlated and analysed using wide-field techniques) is pretty well like any connected element array data set! Phase stability and coherence times are essentially infinite.

From a technical perspective the message is clear: (i) With sustained data rates of 1 Gbps, Global VLBI can approach, in some cases surpass, the rms noise levels attained by connected element arrays and (ii) every VLBI target field can be self-calibrated at frequencies $\sim 1 - 3$ GHz, provided a wide enough field of view can be maintained, and sufficient computing resources are available to cope with the enormous data sets implied.

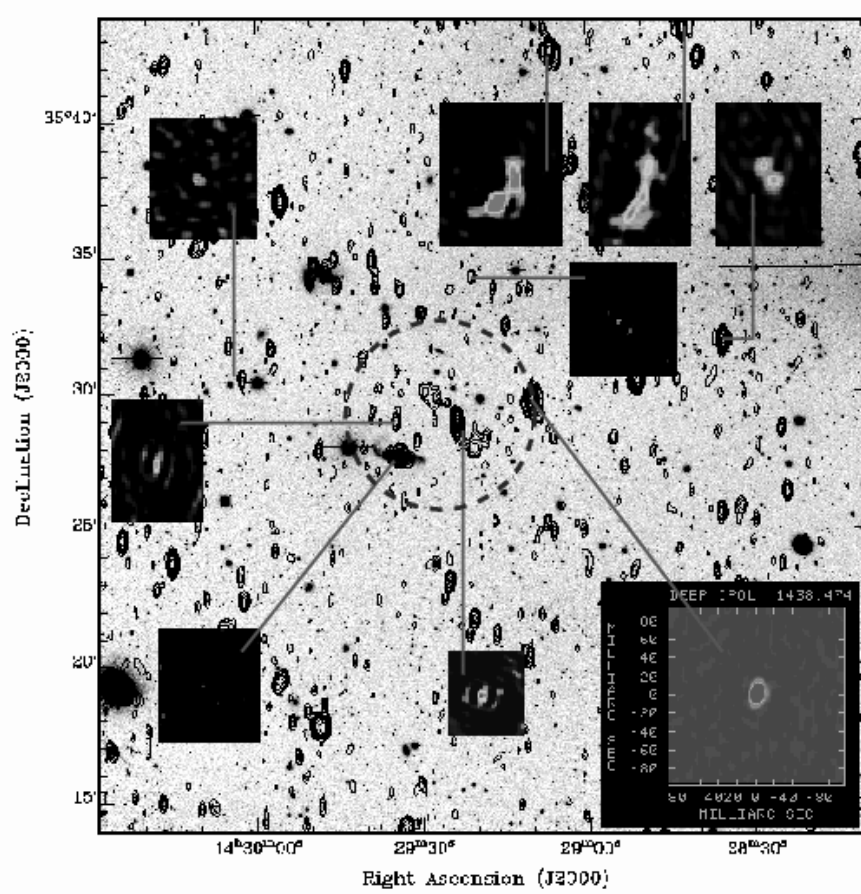


Figure 9. Deep VLBA+GBT 1.4 GHz observations of a small portion of the NOAO-N Bootes deep field. The VLBI detections are shown inset. Radio line contours (produced by the WSRT) are superimposed on the NOAO optical field). One non-detection is also shown (bottom left) - a bright, presumably nearby spiral galaxy that is well detected by the WSRT (around the few mJy level). Very likely the radio emission from this system is associated with extended star formation. These are the deepest images made with VLBI to date (Garrett, Wrobel & Morganti in preparation).

Once systems like PCInt become available, the bottleneck quickly moves towards the problem of handling the enormous data sets that such systems can generate. Clusters of Linux PCs are the only feasible solution today, together with massive storage devices. Access to GRID like computing resources may be the only feasible short-term solution.

8. A personal view of the future

The sensitivity of both mm and cm-VLBI is set to improve dramatically. In the next 5-10 years, Gbps data rates will be routine, coherence times will be virtually unlimited and the first real-time eVLBI production networks will begin to be realised. As network performance is continuously monitored, serious telescope failures will be rare, and feedback immediate. Target of Opportunity observations (e.g. GRBs) will be possible even for part-time arrays such as the EVN. Frequency bands will be configurable and blind searches for spectral features in the data will be possible. Wide-field imaging will be the norm, and several dozens of sources will be detected and imaged simultaneously, in any given observing run. Huge VLBI source surveys will be conducted without relying on the biased selection criteria employed in major surveys today. The resulting wide-field data sets will be usefully mined by Virtual Observatory facilities, providing on-the-fly images and spectra of particular regions of sky.

The whole process of doing VLBI will be irrevocably changed, and the scientific base of our observations expanded immeasurably. We can look forward to an era in which, for the first time, VLBI observations will be made, correlated and automatically pipelined all within the same day!

I'd like to thank Young Chol Minh and the rest of the LOC for their hospitality and congratulate them on organising and hosting an excellent meeting.

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